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ORIGINAL PAPER

Combined impacts of different irrigation levels and potassium doses on drip-irrigated pomegranate yield, quality, water productivity, cracking rate, and the economic net return

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Abstract

The objective of the present study was to investigate the impacts of potassium and different levels of irrigation on the yield, cracking, quality, net economical return, and water consumption of the pomegranate (*Punica granatum L.* -cv. Hicaznar), and was carried out at the Alata Horticultural Research Institute in 2012, 2014, and 2015 growing season in the Eastern Mediterranean region of Turkey. The main plots and subplots were set up as the potassium doses (K_0: 0 g/tree; K_1:300-350-400 g/tree; K_2:600-650-700 g/tree) and irrigation level (I_{75}:0.75; I_{100}:1.00; I_{125}:1.25). An experiment was a split-plot design with three replications for the arrangement and analyses of the aforementioned 9 treatment combinations. Irrigation was conducted when the cumulative evaporation was found to be 30 ± 5 mm. According to the experimental results, the potassium and the irrigation levels were found to profoundly affect the total pomegranate yield and yield components at a statistical error of 1% and 5%. The lowest yield was found to be at K_0I_{75}, and the highest yield was found to be at K_1I_{125} for all 3 years. It was observed that lower irrigation levels led to lower yield. When irrigation levels were studied concerning potassium levels, the I_{75} level was found to produce the lowest yield. The total irrigation water for all treatments was 254–416 mm and the seasonal evapotranspiration (ET) was 387–670 mm according to the treatment. It was illustrated that potassium dose and irrigation levels significantly influenced water productivity (WP) and irrigation water productivity (IWP). The lowest level for WP was 4.77 kg m^{-3} at the K_0I_{125} level, and the highest level for WP was 9.54 kg m^{-3} at the K_1I_{75} level. The lowest level for IWP was 6.84 kg m^{-3} at the I_{125} level, and the highest level for IWP was 13.49 kg m^{-3} at the I_{75} level. The potassium and irrigation levels were found to affect the pomegranate yield, cracking rate, and amount of fruit, as well as parameters that represent quality, such as fruit rind thickness and amount of aril, at a statistically significant level. As a result, K_1I_{125} levels can be recommended for a high amount of yield in the field of pomegranate cultivation with drip irrigation. The WP, IWP levels, total yield, waste yield levels, and economic net return support the use of K_1I_{100} irrigation in conditions of drought. Over the 3-year combined economic analysis, the K_1I_{125} treatment produced the maximum net income followed by the K_1I_{100} treatment.

Introduction

Turkey is one of the world's major pomegranate-producing countries and has made considerable progress in pomegranate production, processing, and marketing (Ozguven et al. 2015). It is estimated that the world pomegranate production area is more than 835 950 ha (Pienaar 2021). Total pomegranate production in Turkey reached approximately 647 676 tons in 2021. Turkey is also among the leading countries globally in pomegranate export which increased by 184 333 tons in 2021 (TUIK 2022).

Pomegranate was grown mostly in the Mediterranean and Aegean regions but increased in the Southeast Anatolia Region and some microclimate regions. Pomegranate, which is specially processed in the fruit juice industry, has been extensively used in the hand of other pomegranate products in Turkey. It has been detected in different problems in growing pomegranates together with an increasing plantation (Yılmaz and Ozguven 2019).

It is known that Mersin has low annual precipitation in the semi-arid region of Turkey and requires a significant

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amount of irrigation water due to insufficient rainfall during the peak growing season. Since the yield of pomegranate is significantly affected by water scarcity, supplemental irrigation is required during the growing period. Furrow irrigation is one of the traditional surface irrigation methods frequently utilized in Turkey without taking into consideration the actual consumption of pomegranate requirements. In young gardens, one row of furrows passed on both sides of the rows, and two furrows in old gardens provide sufficient water for active roots. These practices have created some problems such as excessive irrigation leading to high water losses and low irrigation efficiencies resulting in drainage and salinity issues.

Water is getting scarce both qualitatively and quantitatively in arid and semi-arid regions as well as areas with abundant rainfall. Furthermore, it is expected that climate change will inescapably bring about even more serious droughts in the near future. Because the availability of water for agricultural use is the main challenge for optimal fruit tree cultivation in Mediterranean regions. Accordingly, efficient use of the limited freshwater resources available in irrigated agriculture necessitates the use of drip irrigation systems, which minimize water losses, provide water and energy savings, and relatively decrease environmental pollution while increasing product yield and quality, thus ensuring that the water resources of the country are used in a more efficient manner (Sezen et al. 2019).

The cracking of pomegranate fruits is one of the biggest problems, especially limited to arid or semi-arid regions of the world, creating an important limit on crop productivity, quality, and a high amount of yield loss. As a result of fruit cracking in pomegranate, even more, than half of the product can be lost (Blumenfeld et al. 2000; Singh et al. 2020).

Researchers have pointed out many factors about the causes of fruit cracking in pomegranates. The primary causes of fruit cracking in pomegranates are genetic factors, irregular irrigation, temperature fluctuation in day and night, heavy and prolonged rains during harvest time, delay of harvesting, high evapotranspiration, low humidity, and fluctuating soil water levels (Cheema et al. (1954); El-Rahman 2010; Meshram et al. 2010; Hoda and Hoda 2013; Galindo et al. 2014; Khadivi-Khub 2015; Bakeer 2016; Singh et al., 2020; Volschenk 2020). Further factors are shortages or unbalance of some plant nutrients (especially N, K, Ca, and B), sunburn on fruit skin, russeting, fruit skin injuries, abnormally shaped fruits, and some pathogenic causes (Galindo et al. 2014; Saei et al. 2014; Hamouda et al. 2015; Davarpanah et al. 2018; Yılmaz and Ozguven 2019; Mokhtarzadeh and Shahsavar 2020; Sing et al. 2020). The cracking is more visible at the maturity stage of the fruits, and the most effective factor in cracking is due to the imbalance between the existing moisture in the soil and the current water situation in the plant (El-Rahman 2010; Meshram et al. 2010; Galindo et al. 2014; Volschenk 2020). According to Singh et al. (2020), a rapid drop in soil moisture induces water stress, which negatively influences fruit production and contributes to fruit cracking. The pomegranate cultivars have remarkable differences in sentiment and drag to fruit cracking. Saad et al., (1988) reported that there is no single solution to prevent cracking in pomegranate fruit and the cracking rate varies depending on the variety, heredity, climatic conditions, cultivation technique, and fruit development.

Potassium, which plays a vital role in the metabolic, physiological, and biochemical functions of the plant, has the most important place among macronutrients compared to other plant nutrients, and in its deficiency, the plant gets more stress related to water deficiency by receiving less irrigation water results in cracking in pomegranate (Sheikh and Manjula 2006; Saei et al. 2014; Chater and Garner (2018); ; ; ; ; Mokhtarzadeh and Shahsavar 2020; Lester et al. 2010). Potassium deficiency has been observed in sandy-loam soils (Phene et al. 1989), especially with increasing soil depth increases. Al-Obeed, (2001) reported that regular potassium application was necessary to obtain a high yield and best fruit quality of pomegranate cultivars. Increasing the rates of potassium sulfate applications markedly increased the yield and the most of physical and chemical fruit properties.

Even though pomegranate has good drought resistance; high yield and large unit fruit weight can still be attained only through regular irrigation practices (Holland et al. 2009; Parvizi and Sepaskhah 2015; Fialho et al. 2021). Various studies have been conducted illustrating the possible adverse impacts or favorable effects of water stress on pomegranate fruit quality (Khattab et al. 2011; Laribi et al. 2013; Centofanti et al. 2017; Martínez-Nicolas et al. 2019; Volschenk 2020). It has been presented by Mellisho et al. (2012) that medium levels of water stress led the fruits to display decreased fruit growth, bringing about an inferior final fruit size and inferior pomegranate yield coupled with alters in fruit chemical characteristics that are indicators of earlier ripening. Although there is no indication of thirst in fruit growing cultivated annually in our region, early yield or drought caused by time causes significant yield decreases caused by water deficit. In pomegranate, there is little detail on the combined effects of irrigation and potassium on fruit cracking, and very little is known about the impact of different irrigation levels (I) and potassium doses (K) on fruit cracking using full and deficit irrigation regimes in drip irrigation systems. As a result, the goals of this study were to (i) investigate the effects of various potassium dose and irrigation levels on soil water delivery, fruit yield, pomegranate cracking volume, WP, IWP, and net economical return, and (ii) produce the right potassium dose and irrigation standard for the Hicaznar variety of pomegranate under drip irrigation.

Materials and methods

Study site and climate

The research was carried out for 3 years (2012, 2014, and 2015) in a pomegranate orchard of Alata Horticultural Research Institute located in the Erdemli district of Mersin province in Turkey, which is located between the Taurus Mountains and the Mediterranean coast at 36°37' N latitude and 34°20' E longitude and its height from the sea level is 4 m. Over the 3-year study, all climatic data used in the study were obtained from the Alata Horticultural Research Institute meteorology station (iMETOS 3.3, Pessl Instrument, Austria) located next to the experimental plot (Table 1). Long-term climate data (1966–2015) were obtained from Adana Meteorology Regional Directorate. In all experimental years, growing season temperatures were typical of long-term means at Erdemli, Mersin. The climate of the study area is semi-arid type, characterized by warm and rainy winters and hot and dry summers. The long annual temperature average in the region is 18.5 °C, the relative humidity average is 68%, and the annual evaporation is 1328 mm. The highest evaporation is in August with 198 mm. The amount of rainfall from bud awakening to harvest in the first growing season of the pomegranate was 101 mm, which is 54% of the long-term average precipitation. In the same period of the second and third year, rainfall was 260 and 79 mm, which was 138% and 42% of the long-term average rainfall values, respectively.

Table 1 Historical monthly mean and growing season climatic data of the experimental area

Years	Climatical parameters	Months											
		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
2012	Maximum temperature °C	13.9	14.6	16.5	22.6	32.0	37.4	36.1	34.9	35.2	35.9	27.3	18.1
	Mean temperature (°C)	8.6	9.2	11.3	16.7	20.6	25.2	28.4	28.7	26.2	21.5	16.5	11.5
	Maximum humidity (%)	87.5	89.6	80.7	84.1	80.4	74.3	75.1	71.5	74.3	83.5	92.2	92.2
	Mean humidity (%)	71.8	62.8	61.0	72.4	71.0	68.6	69.0	62.9	62.4	62.8	69.2	72.9
	Maximum wind speed (m s^{-1})	2.0	2.4	3.1	2.7	2.4	2.5	2.2	2.2	2.0	1.9	1.9	2.6
	Mean wind speed (m s^{-1})	1.1	1.3	1.6	1.5	1.4	1.7	1.5	1.6	1.5	1.1	1.0	1.3
	Mean monthly evaporation (mm)	25.4	58.7	94.7	128.0	131.1	180.4	176.0	197.0	138.1	102.2	55.1	25.0
	Rainfall (mm)	195.0	65.0	55.2	18.6	15.2	6.4	3.6	0.0	2.0	75.8	165.0	190.8
2014	Maximum temperature °C	19.1	23.0	26.1	31.8	29.7	35.5	33.2	33.2	33.0	32.1	25.8	22.1
	Mean temperature (°C)	11.5	11.9	14.6	16.8	20.4	24.2	24.2	28.5	25.6	20.3	15.1	13.5
	Maximum humidity (%)	92.9	83.6	86.5	87.2	81.9	82.4	73.5	75.1	75.9	76.8	87.8	86.9
	Mean humidity (%)	67.7	64.8	66.1	67.3	72.8	69.4	69.4	70.7	62.0	65.0	55.4	69.3
	Maximum wind speed (m s^{-1})	1.6	2.1	2.8	2.9	2.4	3.2	2.3	2.5	2.4	1.4	2.5	2.7
	Mean wind speed (m s^{-1})	1.1	1.3	1.6	1.6	1.5	1.7	1.7	1.5	1.6	1.1	1.2	1.3
	Mean monthly evaporation (mm)	43.4	60.0	100.2	134.5	160.7	187.0	203.1	186.2	116.0	97.9	59.2	33.6
	Rainfall (mm)	113.2	22.6	60.8	13.0	115.4	18.4	0.0	11.8	40.8	43.4	71.0	48.2
2015	Maximum temperature °C	20.2	21.8	26.5	27.7	35.4	32.2	33.2	37.8	36.7	28.0	23.3	17.8
	Mean temperature (°C)	9.6	10.8	13.7	15.5	21.4	24.5	27.7	28.8	27.0	22.1	16.7	11.4
	Maximum humidity (%)	91.2	88.9	85.1	85.1	76.8	74.3	72.5	71.9	73.7	86.1	86.3	74.4
	Mean humidity (%)	65.2	69.4	65.7	63.2	63.9	67.9	69.1	64.5	64.7	62.4	50.9	55.1
	Maximum wind speed (m s^{-1})	2.9	3.3	2.0	4.2	3.4	2.3	2.1	2.3	1.6	1.5	1.8	1.8
	Mean wind speed (m s^{-1})	1.4	1.6	1.3	1.6	1.5	1.7	1.5	1.5	1.2	1.0	1.2	1.2
	Mean monthly evaporation (mm)	31.4	34.9	83.9	110.0	158.8	175.1	194.0	180.2	162.4	102.6	79.9	47.2
	Rainfall (mm)	80.2	165.4	43.4	31.4	0.2	0.4	2.6	1.4	0.0	15.2	27.8	11.2
Long Term*	Mean temperature (°C)	9.9	10.2	12.6	16.5	20.9	25.1	28.3	28.5	24.8	20.5	14.3	10.6
	Mean humidity (%)	64.7	61.7	66.8	73.1	71.3	72.0	73.8	68.8	63.8	60.9	72.8	72.1
	Mean wind speed (m s^{-1})	1.2	1.4	1.5	1.5	1.5	1.7	1.6	1.6	1.4	1.2	1.1	1.3
	Mean monthly evaporation (mm)	39.4	46.9	77.2	106.7	146.9	176.1	197.1	193.9	147.0	104.7	63.9	41.7
	Mean rainfall (mm)	110.9	80.2	56.9	40.6	23.5	8.8	3.6	3.2	9.4	42.6	83.3	110.7

(*) 1966–2015

Soil and water properties

Table 2 lists several characteristics of the experimental soil. The soil at the experimental site has a sandy-loam composition in the soil profile, a pH range of 7.88–7.99, electrical conductivity of the saturation extract 0.9–1.30 dS m^{-1}, and gravimetric soil water contents at field capacity (FC) and permanent wilting point (PWP) of the root zone of 7.67–14.77% and 4.72–9.49%, respectively. Mean bulk density varies from 1.59 to 1.61 g cm^{-3}. The undisturbed soil samples were capillary saturated and equilibrated to field capacity (FC) (− 1/3 bar) matric potentials in a pressure plate (Klute 1986). Soil moisture at − 15 bar matric potential permanent wilting point (PWP) was assigned using disturbed soil samples (Klute 1986). Available water (AW) content was calculated as the difference between volumetric water content at FC and PWP in the 0.90 m soil profile. The bulk density (As) was acquired using the core method described by Blake and Hartge (1986). The organic matter (OM) content was assigned using the Walkley–Black Method (Nelson and Sommers 1996). Soil reaction (pH) and electrical conductivity (EC) were determined at the same soil water suspension 1:1 (*W*: *V*) by pH meter and electrical conductivity bridge, respectively (USDA 1954). Available potassium in the soil profile was established by the flame-photometer method. The exchangeable potassium levels in the soil are 104.22 ppm in 0–30 cm, 39.90 ppm in 30–60 cm, and 15.90 ppm in 60–90 cm. In the 90 cm soil profile, the usable water-holding capability of the soil is 67 mm. Water is obtained from a deep well in the experimental field, with a quality rating of (C_3S_1: high salinity and low sodium class) by USSL (1954), a pH of 7.32–7.34, and a mean electrical conductivity (EC) of 0.82 dS m^{-1}, both of which are suitable for the pomegranate.

Experimental details

The experiment was laid out in a split-plot design with 3 potassium doses as the main plot treatments (K_0: 0 g $tree^{-1}$; K_1: 300 g $tree^{-1}$ and K_2: 600 g $tree^{-1}$), and 3 irrigation water levels ($I_{75} = 0.75$, $I_{100} = 1.00$, and $I_{125} = 1.25$ treatments) as the sub-treatments with 3 replications. I_{75}, I_{100}, and I_{125} treatments received 75, 100, and 125 of cumulative class A pan evaporation (CPE).

The research was carried out on the 6-year-old Hicaznar cultivar, which is widely grown for pomegranate cultivation worldwide, for 3 years in 2012, 2014, and 2015. There are 5 pomegranate trees on each plot, and the spacing pattern for pomegranates was 5 m × 3 m (Fig. 1).

A pressure gauge and flow meter were mounted in the control unit to assess the desired water depth and pressure. Double drip laterals are mounted parallel to the tree rows, 35 cm on both sides, and inline drippers (2 l h^{-1}) are spaced 40 cm apart along the axis.

Agronomic practices

In irrigation applications, daily evaporation values were taken from the Class A pan placed by the standards in the experimental area. When roughly half of the available soil water in the 90 cm soil profile had been consumed, the first irrigation was applied. Then, subsequent irrigation was applied when the cumulative evaporation in the Class A pan reached 30 ± 5 mm. In irrigation levels, I_{75}, I_{100}, and I_{125} irrigations were applied at the rates of 75, 100, and 125% of cumulative class A pan evaporation on the same day, respectively. The percentage-wetted area was taken as 40% to calculate the irrigation water to be applied (Dinc et al. 2018). Each treatment was replicated three times in all years. The last irrigations for pomegranate trees were applied on the day of the year (DOY) 267 in 2012, DOY 265 in 2014, and DOY 272 in 2015.

In fertilization, nitrogen in the form of ammonium nitrate, phosphorus in the form of superphosphate, and potassium in the form of nitrate were applied through fertigation which was divided between February and July of each experimental year.

In the fertigation method, a tank system operating with pressure differences was used. The quarter rule proposed by Burt et al. (1995) was used as a guideline for applying fertigation. According to this rule, the total amount of water to be applied in an irrigation set is divided into four equal parts (four quarters). In the first quarter, only water is applied to stabilize the pressure in the pipelines and to wet the upper surface of the soil. During the second and third quarters,

Table 2 Physical and chemical properties of experimental soil

Soil depth (cm)	FC (g g^{-1})	PWP (g g^{-1})	As (g cm^{-3})	Texture class	Salinity (ECe) (dS m^{-1})	$CaCO_3$ (%)	OM (%)	P(mg kg^{-1})	*K* (mg kg^{-1})	pH
0–30	14.02	8.22	1.59	SL	1.30	27.80	2.81	16.0	104.22	7.88
30–60	14.77	9.49	1.59	SL	1.10	32.00	2.62	14.0	39.90	7.97
60–90	7.67	4.72	1.61	SL	0.90	31.20	2.40	11.0	15.90	7.99

FC field capacity, *PWP* permanent wilting point, *As* bulk density, *OM* organic matter

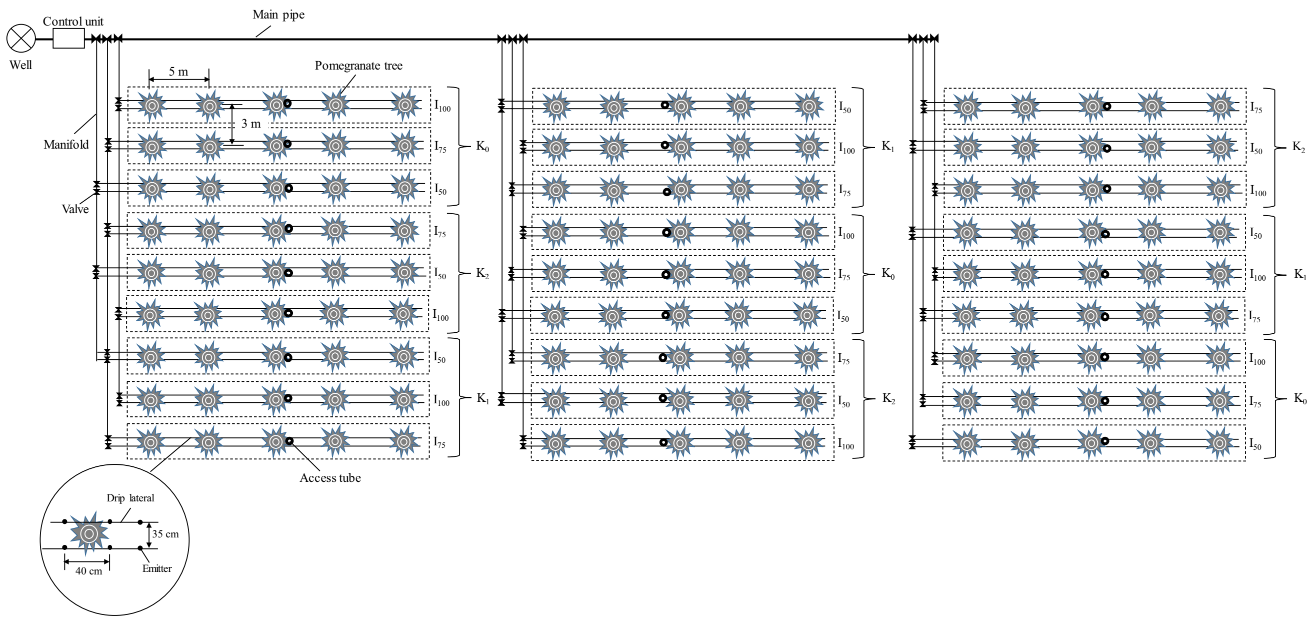


Fig. 1 The layout of the experimental plots, and the location of soil moisture tubes

water and fertilizer are applied together, and in the last quarter, only water is applied again. Thus, it is prevented that fertilizers are washed under the root zone or fertilizer solutions remain in the pipelines at the end of the application. Fertilizers were calculated for each subject in separate sets to avoid any application errors.

In the experiment, ammonium nitrate (33%) and MAP (12-61-0) fertilizers were applied equally to all parcels in nitrogen and phosphorus fertilization applications in all parcels. In potassium fertilization applications, different doses of Potassium Nitrate (13.5-0-45.5) fertilizer were applied to the K_1 and K_2 treatments, but not applied to K_0. The required nitrogen dose was balanced by increasing ammonium nitrate in the K_0 treatment.

Table 3 shows the pure nitrogen, phosphorus, and potassium doses that were applied in 2012, 2014, and 2015. Nitrogen, phosphorus, and potassium fertilizers applied during the growing period of the pomegranate were made in 5 different periods (before the wood buds, at the first flower buds emergence, when 70% of flowering occurs, fruit set, and fruit development period). The difference in potassium doses in K_1 and K_2 treatments during the experimental years is related to the age of the pomegranate trees used in the experiment, and the amount of potassium applied with the increasing age of the pomegranate tree was applied as 50 g per year. Since the pomegranate trees are from a youth age and the trees grow a little more every year, the amount of potassium is increased by 50 g until the full bearing stage. Year-to-year fertilizer dosing on young trees has also been used by other researchers studying pomegranate plant nutrition (Ayars et al. 2017; Dhillon et al. 2011). The application doses of fertilizers were calculated at the rates specified in Table 3 and applied according to the treatments. The data set for the 2013 growing season could not be collected due to pre-harvest extreme storms. For this reason, the 2013 fertilization dose was continued in the following experimental year.

Table 4 summarizes agronomic practices used over 3 experimental years. In the years when the experiment was carried out, soil cultivation was worked out with a hoeing machine. In the cultural struggle in the trees existing in the pomegranate parcel, pruning was done by removing 20–25 cm of the end shoots of the trees and the water sprouts before the wood woke up. Fungicide (Baciroxychloride) was sprayed as a protective measure after pruning. In the development periods after the awakening of the wood buds, weed control was applied as an herbicide (Roundup, Knock Out) pesticide control according to the emergence periods. The bottom shoots of the trees were cleaned 3 times, once a month, with pruning shears. The pesticide fight against aphids that emerged during shoot formation and flowering was done with Acetamiprid (Antroplan) application. Pesticide combat in combating snails emerging in the trunks of trees. In the experiment, the cultural and chemical struggle was made during the growing period from the awakening of the wood buds to harvest, and the procedures for maintenance and control are given in Table 4.

The pomegranate harvest was carried out during the period when the fruit took the color and size specific to the variety, the tips (calyx segments) of the crown of the fruit opened outwards, and the male organ threads on the fruit dried. The pomegranate fruits were harvested on November 13, 2012,

Table 3 Fertilizer application dates and pure dosage amounts by experimental years (2012, 2014, and 2015)

Experimental years	Number of Applications	Application times	Pure dose amount of fertilizer (g tree^{-1})				
			N	*P*	*K*		
					K_0	K_1	K_2
2012	1	January 28	60	75	0	60	120
	2	April 06	90	38	0	45	90
	3	May 15	75	37	0	45	90
	4	June 15	45	0	0	120	240
	5	July 15	30	0	0	30	60
	Total		300	150	0	300	600
2014	1	January 29	70	87	0	70	130
	2	April 18	105	44	0	53	98
	3	May 18	87	44	0	52	97
	4	June 17	53	0	0	140	260
	5	July 16	35	0	0	35	65
	Total		350	175	0	350	650
2015	1	January 19	80	100	0	80	140
	2	April 22	120	50	0	60	105
	3	May 20	100	50	0	60	105
	4	June 12	60	0	0	160	280
	5	July 12	40	0	0	40	70
	Total		400	200	0	400	700

October 15, 2014, and October 15, 2015. Total fruit yield (kg ha^{-1}) was determined by harvesting all the fruits on the three trees.

Measurements

Soil water content (SWC)

Before irrigation, the SWC was determined at 0.15 m from the dripper using a profiled probe (Aqua Check Soil Moisture Management MobiCheck) and gravimetric method. Soil auger samples were collected at intervals of 0.3 m up to 0.9 m in the soil profile before each irrigation. UTW-0633 model digital balance was used to weigh the soil samples, and the UTD-1295 Laboratory Oven (UTEST Corp., Ankara, Turkey) was used to determine the oven dry weight in the soil. Three replications of each procedure were taken during all growing seasons before harvest. Profile probe measurements were calibrated at 0–0.30, 0.30–0.60, and 0.60–0.90 m soil profiles according to the soil water content determined gravimetrically. Also, monitoring the soil water content in 0.90 m–1.2 m in the plots revealed that deep percolation below 90 cm depth was negligible.

Table 4 Agronomic maintenance and management practices carried out during the experiments in 2012, 2014, and 2015

Observations	Experimental years		
	2012	2014	2015
Tillage and weed control	Feb. 01	Jan. 28	Feb. 03
Pruning	Feb. 24	Feb. 20	Feb. 27
Fungicide spraying	Feb. 26	Feb. 22	March 01
Disease and pest control	March 18	March 15	March 21
Weed control	May 25	June 08	June 02
	July 01	July 17	July 10
	August 12	August 14	August 18
Pruning of bottom shoots	May 26	June 10	June 05
	July 17	July 19	July 11
	August 25	August 15	August 18

Evapotranspiration values (ET), water productivity (WP), and irrigation water productivity (IWP)

To determine the root depth and distribution to be used in evapotranspiration at the beginning of the experiment, roots were taken from the trunk of 3 pomegranate trees, 0.5 m radial distance, 0.30 m intervals, and till 0.90 m soil deep. The highest root density was observed in 0–0.30 m soil depth (63.50%), which was decreased to 27.75% on a dry weight basis at 0.30–0.60 m. It reached the lowest value (8.78%) at 0.60–0.90 cm in depth. As a result, the root system is shoaly in a pomegranate tree as below 0.60 m soil depth, not much root activity was determined.

The actual crop evapotranspiration (ET) was estimated using the soil water balance method, which involved assessing the changes in the SWC in a 0–0.90 m soil layer over some time as follows (Allen et al. 1998):

$$ET = I + R \pm \Delta S - Dp - Rf,$$

where ET is the actual evapotranspiration (mm), I is the irrigation water volume (mm); R is the rainfall (mm); ΔS is the change in soil water storage (mm); Dp is deep percolation (mm); and Rf is the runoff. Dp and Rf were believed to be marginal, since the volume of irrigation water was regulated and the groundwater table was lower than 5 m. Dp was specified to be zero, because there were insignificant changes in the SWC under 0.9 m soil depth, and the SWC beyond 0.9 m soil depth was well under the field capacity.

In seasonal ET calculations, each irrigation event was taken into account separately as a time scale, and the seasonal ETc value was calculated by summing them up. Seasonal ET values were calculated between 15 March 2012 and 20 November 2012 (first year), 15 March 2014 to 20 November 2014 (second year), and 16 March 2015 to 20 November 2015 (third year) during the experimental years.

The amount of irrigation water (I) was calculated using the following equation:

$$I = CPE \times P \times IL \times A,$$

where I is the irrigation water amount (l), CPE is the cumulative pan evaporation (mm), P is the percentage of the wetted area (taken as 40% for pomegranate), and IL is the irrigation water levels (0.75, 1.0, and 1.25). The values of IL evaluated as plant-pan coefficients ($K_{cp1} = 0.75$, $K_{cp2} = 1.00$ and $K_{cp3} = 1.25$), K_p is the coefficient of pan evaporation (i.e., $K_p = 1.00$), and A is the plot area (m^2).

Irrigation treatments were based on the evaporation data (Epan, mm) obtained from a Class A Pan located near the experimental area. Irrigation is scheduled every time the cumulative evaporation value reaches 30 mm. In each irrigation, cumulative evaporation (30 mm) was multiplied by the plot size (15 m^2) and the wetted area percentage (0.40) to acquire the amount of irrigation water (in liters) applied to the I_{100} treatment.

Pomegranate yield was split by seasonal ET and the overall amount of water applied to calculate WP and IWP values (Fernandez et al. 2020).

Fruit physical characteristics and the growth stages of pomegranate

Four fruits were incidentally selected from each replication to determine the physical characteristics of the pomegranate fruits. Fruit weight was weighed with electronic scales and fruit skin thickness was measured from the middle part of the peel surrounding the arils by dividing the fruits into two parts using a digital caliper with an accuracy (Mitutoyo Corp., Kawasaki, Japan) of ± 0.01 mm (Passafiume et al. 2019). Measurements were replicated in at least 3 points of each fruit. The number of cracked fruit on each tree was counted and the results were stated as the percentage of fruit influenced by cracking. Four replicates per treatment and year were accomplished for all physical parameters. Different phenological growth stages of pomegranate and the time taken to harvest were reported by day of the year (DOY) (Melgarejo et al. 2000).

The economical assessment

The economic analysis may accomplish as a decision support tool for regional and on-farm system management to improve strategy scenarios for sustainable farming systems. The economic assessment was exerted using the partial budgeting technique to specify the highest net income, which was calculated by subtracting all the production costs from gross incomes per hectare for all treatments (Sezen et al. 2019). Partial budgeting can be useful in the decision process farm owners and managers use to decide on alternative uses of resources they have in their businesses. In this study, considering all of the production costs and inputs for pomegranate production were the same except for labor costs for irrigation, water cost, and K fertilizer cost in all treatments. All current prices and costs are taken from open market conditions.

Statistical analysis

On the recorded results, the experiment was managed in a split-plot design having K dose in the main plot, while the irrigation level in the sub-plot had three replications for each experimental year. The data were statistically analyzed using the SPSS software package (V19.0). The least significant differences approach (LSD) was used as the mean separation test (Snedecor and Cochran 1989).

Results and discussion

Soil potassium content

The available soil potassium levels at the start of the experiment in the orchard in which the experiment was conducted are presented in Table 2. At the beginning of the experiment, available potassium amounts were determined as 104.22 mg kg^{-1} in the 0–30 cm profile, 39.90 mg kg^{-1} in the 30–60 cm profile, and 15.90 mg kg^{-1} in the 60–90 cm profile (Table 2). As a result of the 3-year experiment, when the potassium change in the soil profile (0–30 and 30–60 cm) was examined in 2015, it was determined that there was a decrease in K_0 application but a dramatic increase in K_1 and

K_2 applications according to the potassium levels of the soil in 2012 (Tables 2 and 5). At the beginning of the experiment (2012), the amount of available potassium was determined between 15.90 and 104.22 mg kg^{-1} according to the 60 cm soil depth.

When the K contents in the 60 cm soil profile were examined toward the end of the experiment in 2015, the available K contents increased depending on the increasing irrigation level at each K dose. The lowest K value was determined in the K_o plot, while the highest one was obtained from the K_2 treatment. The content of available K in the soil rose with the rising K dose and increased with the rising irrigation amount. As indicated in Table 5, available K was concentrated at 0–30 cm at all irrigation levels at each K dose**.** At each potassium dose, the amount of available K in the 30–60 cm soil profile accumulated more than the deeper layer, depending on the increasing irrigation level. The highest accumulation amounts were determined at the I_{125} irrigation level at the K_2 dose at the end of the experiment. It shows that higher dose K practice did not induce plants to suck surplus K nutrients, and pomegranate plants had scarce sucking of K nutrients.

Table 5 The potassium contents of the soil at each potassium (K) and irrigation levels (I) toward the end of the experiment in 2015 (0–60 cm)

K dose	Irrigation levels	Soil depth (cm)	K (mg kg^{-1})
K_0	I_{75}	0–30	63.65
		30–60	34.80
	I_{100}	0–30	72.12
		30–60	36.37
	I_{125}	0–30	88.71
		30–60	45.75
K_1	I_{75}	0–30	250.94
		30–60	137.54
	I_{100}	0–30	280.97
		30–60	197.04
	I_{125}	0–30	405.18
		30–60	225.90
K_2	I_{75}	0–30	459.51
		30–60	253.79
	I_{100}	0–30	615.63
		30–60	345.83
	I_{125}	0–30	851.17
		30–60	363.76

K_0, K_1, and K_2: potassium doses, I_{75}, I_{100}, and I_{125}: irrigation levels

The growth stages of pomegranate

Pomegranate growth stages were calculated based on visual observation and reported as a number of days of years (DOY) over the 3-year study (Table 6). During the development period of pomegranate (cv. Hicaznar), wood buds generally begin to wake up at the beginning of March. The first flower buds appeared in the second week of April. Flowering started in the first week of May and continued until the first week of July (Table 6). Fruits have completed their growth and ripening period between July and October. Irrigation during the growing period started in mid-May and was discontinued 15 days before harvest. The total length of the growing season of pomegranate was 217, 219, and 220 days, respectively, for 2012, 2014, and 2015 experimental years (Table 6). Gradually rising water stress under K_0 dose and deficit irrigation (I_{75}) conditions resulted in shorter growing seasons compared to I_{100} and I_{125} treatments. There were no statistically significant differences in terms of development periods between other K doses (K_1 and K_2) and irrigation levels (I_{100} and I_{125}) in 2012, 2014, and 2015. The decrease in fruit yield at I_{75} irrigation levels exposed to water stress during the fruit ripening stage (DOY 286 in 2012, DOY 282

Table 6 Phenological observations in the development period of pomegranate

The growth stages of pomegranate	Experimental years					
	2012	DOY	2014	DOY	2015	DOY
Bud bursting	10.03.2012	69	10.03.2014	68	09.03.2015	67
The appearance of the first flower buds	10.04.2012	100	07.04.2014	98	12.04.2015	101
The appearance of the first flower (5%)	08.05.2012	128	07.05.2014	126	04.05.2015	121
Occurrence of flowering (70%)	26.05.2012	146	28.05.2014	147	24.05.2015	143
First irrigation	24.05.2012	144	26.05.2014	145	20.05.2015	138
End of flowering	05.07.2012	186	01.07.2014	181	08.07.2015	188
Last irrigation	24.09.2012	267	23.09.2014	265	30.09.2015	272
fruit maturity	13.10.2012	286	10.10.2014	282	12.10.2015	284
Harvest	13.10.2012	286	15.10.2014	287	15.10.2015	287
Yellowing of leaves	10.11.2012	314	13.11.2014	216	12.11.2015	215
Falling of leaves	17.12.2012	351	22.12.2014	355	19.12.2015	352

DOY days of the year

Table 7 LSD grouping regarding the yield of pomegranate in potassium dosages and irrigation levels (2012, 2014, and 2015)

Experimental years	Pomegranate yield (kg ha^{-1})							
	Potassium dosages			LSD (0.05)	Irrigation levels			LSD (0.001)
	K_0	K_1	K_2		I_{75}	I_{100}	I_{125}	
2012	25013	31947	32880	6951.3	27050 c	29940 b	32860 a	2534.5
2014	28560 b	36110 a	30870 b*	4199.7	28820 c	31870 b	34840 a	2610.0
2015	30630 b	37740 a	33740 ab*	3818.8	30400 c	33460 b	38250 a	2551.9
Source	df	Prob	Source	df	Prob	Source	df	Prob
2012			2014			2015		
K	2	0.0844 ns	K	2	0.0175*	K	2	0.0168*
I	2	0.0012**	I	2	0.0011**	I	2	0.0011**
KxI	4	0.5895 ns	KxI	4	0.9967 ns	KxI	4	0.5189 ns

ns: non-significant, K_0, K_1 and K_2: potassium doses, I_{75}, I_{100} and I_{125}: irrigation levels, *Significant at $P<0.05$, **Significant at $P<0.01$

in 2014, and DOY 284 in 2015) confirmed the assumption that fruit maturity is a sensitive stage in fruit yield in pomegranate. Current findings conform to the results of previous studies (Intrigliolo et al. 2013; Laribi et al. 2013).

Pomegranate yield

It was observed based on the analysis of variance that while there was no statistically significant difference between potassium doses on the pomegranate yield in 2012, a significant difference was identified at the 5% error level in 2014 and 2015. LSD grouping regarding the yield values of potassium doses during the experimental years is given in Table 7. According to the potassium dose, pomegranate yield varied from 25,013 kg ha^{-1} (K_0) to 32,880 kg ha^{-1} (K_2), 28,560 kg ha^{-1} (K_0) to 36,110 kg ha^{-1} (K_1), and 30,360 kg ha^{-1} (K_0) to 377,740 kg ha^{-1} (K_1), in 2012, 2014, and 2015, respectively (Table 7). At the 5% level of importance, LSD classification shows that K_1 treatment was in the first category and K_0 was in the last group in all experimental years. Thence, inadequate potassium amount is contemplated to be a grave limiting factor for pomegranate yield. (Table 7). Many researchers enrolled a rise in pomegranate yield as a consequence of increasing the potassium dose. Such rises in the pomegranate yield were either due to the formation of great-sized fruits or a rise in the number of fruit per tree or both. Also, the interactions between potassium dose and irrigation level were not found statistically significant in all years. However, it was determined that increasing potassium doses at each irrigation level had a significant positive effect on yield increase. While there was no statistical difference in pomegranate yield in 2012 in terms of K dose, the yield increased up to the K_1 dose, and then, it was observed that the yield decreased at the K_2 dose in 2014 and 2015 (Table 7). The high potassium dose impeded photosynthetic transfer to the fruit, which may have averted further pomegranate yield increases.

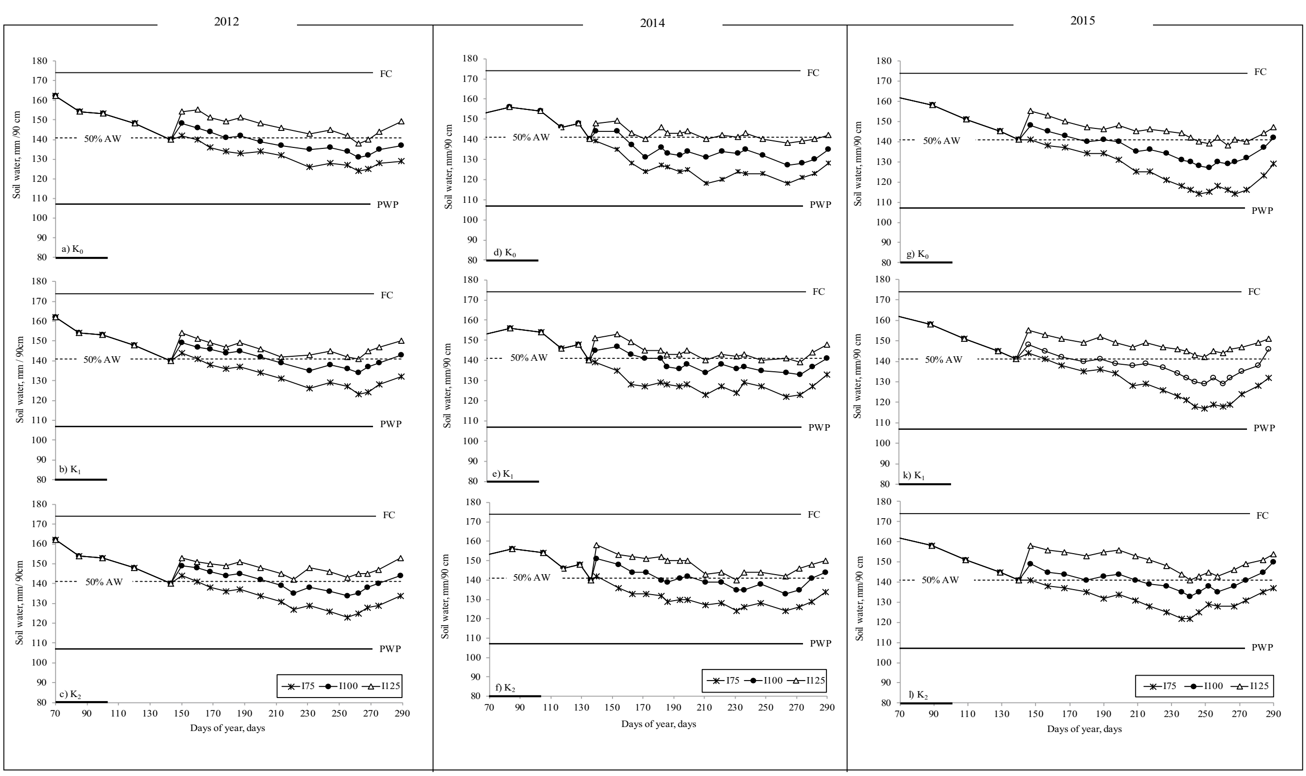
The study of variation in 3 experimental years among irrigation levels revealed that irrigation levels had a major impact on pomegranate yield at the 1% error level in both years, revealing an improvement in pomegranate yield with increasing irrigation water. LSD grouping regarding the yield values of irrigation levels during the experimental years is given in Table 7. According to the irrigation level, pomegranate yield varied from 27,050 kg ha^{-1} (I_{75}) to 32,860 kg ha^{-1} (I_{125}), 28,820 kg ha^{-1} (I_{75}) to 34,840 kg ha^{-1} (I_{125}), and 30,400 kg ha^{-1} (I_{75}) to 38,250 kg ha^{-1} (I_{125}), in 2012, 2014, and 2015, respectively (Table 7). Our findings show that pomegranate fruit yield increases significantly with the increase of irrigation water at each K dose. Based on the LSD test (Table 7), the I_{125} treatment was situated in the first group ($P<0.05$), while the I_{75} treatment was fallen into the last group in all years. In 2012, 2014, and 2015,

K_0I_{75} produced the least amount of fruit. Despite this, pomegranate fruit yield was reduced by 8.9, 8.5, and 12.5% as compared to K_1I_{125} in 2012, 2014, and 2015, respectively, since the K_1I_{100} treatment obtained approximately 18.2, 18.3, and 18.2% less water than the K_1I_{125} plot (Table 7). In the deficit irrigation treatment (I_{75}) involved in each potassium dose, the healing impact of K fertilizer was adorable, but it was not sufficient to compensate for the difference in pomegranate fruit yield.

Generally, the decrease in fruit yield on pomegranates may be based on the effects of water stress on fruit yield components such as the number of fruits per tree and fruit weight. Our results are in line with the findings of Holland et al. 2009; Meshram et al. (2010), Meshram et al. (2011), Rodriguez et al. (2012), Intrigliolo et al. (2013), Fialho et al. (2021) discovered that pomegranate yield and quality improved as irrigation water was added and water stress decreased. On the contrary, some researchers stated that water stress had a positive effect on fruit yield and quality (Khattab et al. 2011; Mellisho et al. 2012; Laribi et al. 2013; Zhang et. al. 2017). Parvizi et al. (2014) obtained the highest efficiency from the partial root drying (PRD-75) treatment in the deficit irrigation strategy on pomegranate.

Soil water content (SWC)

Irrigation scheduling is a significant undertaking that is intensively performed during the season. Its importance depends on the climate and increases with temperature. Irrigation techniques influence the production of pomegranate trees in terms of crop yield, fruit size, fruit consistency, storability, and long-term productivity. Taking these factors into consideration, appropriate irrigation techniques must be established to increase pomegranate WP. (Meshram et al. 2010). The variations of SWC during 2012, 2014, and 2015 for each K dose are shown in Fig. 2a–l, respectively. Pomegranate trees were irrigated from May 29 to September 24, 2012, in the first year, from June 2 to September 23, 2014, and from May 26 to September 30, 2015. There were significant variations between SWC values of different irrigation levels under each K doses at all times of measurement in experimental years. As shown in Fig. 2, the SWC in all treatments varied from field capacity (FC: 174 mm) to the wilting point (PWP: 107 mm) during the overall experimental years (Fig. 2). However, for the last three-to-four applications before harvesting, the SWC steadily decreased for all treatments by the end of the trial. It is noticed that the SWC in treatment I_{125} remained higher than in I_{75} and I_{100} treatments. During



AW: Available water

Fig. 2 a-l Soil water storage variation during 2012 (a-c), 2014 (d-f), and 2015 (g-l) pomegranate growing seasons in all treatments

2012, 2014, and 2015, the SWC in the I_{100} and I_{125} plots of each K dose stayed above 50% of available water (AW) in most of the pomegranate growth stages. Therefore, the I_{100} and I_{125} treatments accomplished a suitable soil water condition for the pomegranate. On the other hand, available water decreased below 50% in almost all I_{75} plots in each K dose during the growing season after treatment irrigations were started in all experimental years. Regular irrigation, on the other hand, is needed during the reproductive stage, because erratic moisture causes the falling of flowers and small fruits to senesce. A rapid drop in soil water creates moisture stress, which hurts fruit production and contributes to fruit cracking on pomegranates.

Applied irrigation water (I) and evapotranspiration values (ET)

Table 8 displays the average volume of applied irrigation water and total crop ET for each of the experimental years. The 34 mm water in 2012 and 2014, and 33 mm water in 2015 were applied uniformly to all experimental plots. The first irrigation treatment began on May 24, 2012 (DOY 144), the second on May 26, 2014 (DOY 145), and the third on May 20, 2015 (DOY 138). Irrigation was stopped about 15–20 days before the pomegranate harvest. Irrigation treatment was discontinued on September 24, 2012 (DOY 286), for the first year, September 23, 2014 (DOY 287), for the second year, and September 30, 2015 (DOY 287), for the third year.

The seasonal irrigation depth in 2012 ranged from 254 to 400 mm depending on the treatment. Even though 26 irrigation applications were made during the first year, irrigation intervals stayed between 4 and 6 days based on the daily evaporation value. The total irrigation amount ranged from 249 to 393 mm in 2014. In the second year, all treatments were irrigated 26 irrigation times, with an irrigation interval of 4–6 days. The seasonal irrigation depths in 2015 ranged from 263 to 416 mm depending on the treatment. In the third year, a total of 28 irrigation applications were conducted, with irrigation intervals ranging from 4 to 7 days based on the daily evaporation value (Table 8). High temperatures and lower relative humidity compared to previous seasons prompted the application of more irrigation water during the 2015 growing season.

Seasonal ET of pomegranate ranged from 387 mm in K_0I_{75} to 524 mm in K_2I_{125} during the 2012 season; 529 mm in K_0I_{75} to 670 mm in K_2I_{125} treatment plots during the 2014 season; and 368 mm in K_0I_{75} to 528 mm in K_2I_{125} during the 2015 season (Table 8). ET values increased as the water level in each K dose increased in 3 experimental years. Minimum ET at each K dose occurred when water deficit I_{75} was applied, while maximum ET was determined by I_{125} treatment. The seasonal ET of the I_{125} treatment was on average 11.5% and 39.9% higher than the I_{100} and I_{75} treatments during a 3-year trial period (Table 8). ET was heavily dependent on the amount of efficient rainfall, the amount of irrigation, and the difference in soil water storage during the growing season. As a result, seasonal ET values varied over the experimental years in this analysis. At the same irrigation levels, the ET values improved as the potassium dose increased in 2012, 2014, and 2015 (Table 8). Bhantana and Lazarovitch (2010) reported pomegranate ET ranging from 171 to 557 mm; Khattab et al. (2011) reported pomegranate ET ranging from 280 to 600 mm and Ayars et al. (2017) reported that there was a significant difference in the pomegranate ET between treatments, ranging from 645 and 932 for surface drip irrigation to 584 and 843 mm for subsurface drip irrigation. According to Seidhom and El-Rahman (2011), the ET of 9-year-old 'Manfalouty' pomegranate trees in sandy desert soils in Egypt was 483 mm. Our ET results are generally consistent with the above-mentioned study findings.

Table 8 Seasonal evapotranspiration (ET), irrigation (I), rainfall, and change in soil water storage values of pomegranate under different treatments during the study period

Treatments	2012				2014				2015			
	I, mm	ET, mm	R, mm	Δ*S*, mm	I, mm	ET, mm	R, mm	Δ*S*, mm	I, mm	ET, mm	R, mm	Δ*S*, mm
K_oI_{75}	254	387	101	32	249	529	260	19	263	368	79	26
K_oI_{100}	327	452	101	24	321	594	260	13	339	440	79	22
K_oI_{125}	400	519	101	18	393	663	260	10	416	514	79	19
K_1I_{75}	254	388	101	33	249	532	260	22	263	372	79	30
K_1I_{100}	327	456	101	28	321	598	260	17	339	443	79	25
K_1I_{125}	400	522	101	21	393	667	260	14	416	518	79	23
K_2I_{75}	254	392	101	37	249	534	260	24	263	374	79	32
K_2I_{100}	327	459	101	31	321	601	260	20	339	447	79	29
K_2I_{125}	400	524	101	23	393	670	260	17	416	528	79	33

ET evapotranspiration; *I* irrigation, *R* rainfall, Δ*S* soil water storage

Water productivity (WP) and irrigation water productivity (IWP)

High WP and IWP are the clefs to providing the sustainable improvement of agriculture in water-scarcity regions, such as the Southern Mediterranean part of Türkiye. Also, improving WP and IWP in pomegranate is critical for sustainability in the face of rising drought caused by global climate change. Through 3-year experiments, K doses, irrigation levels, and K and I relationships have had a huge impact on WP and IWP values (Table 9). In 2012, 2014, and 2015, the WP concerning potassium dose ranged from 5.55 kg m^{-3} (K_0) to 7.11 kg m^{-3} (K_2), 4.79 kg m^{-3} (K_0) to 6.04 kg m^{-3} (K_1), and 6.97 kg m^{-3} (K_0) to 8.58 kg m^{-3} (K_1) (Table 9). At the 5% level of importance, LSD classification shows that K_2 and K_1 treatments were in the first and second groups, and K_0 was in the last group in 2012, 2014, and 2015 (Table 9). Under the same potassium dose, WP and IWP values indicated a downward tendency with the rising in irrigation amount (Table 9). WP and IWP values decreased substantially when the amount of K dose was reduced in both years, according to the LSD test. However, it was determined that increasing potassium doses at each irrigation level had a significant positive effect on yield increase. While an increase in WP and IWP was achieved up to the K_2 dose in 2012, it reached its maximum value in the K_1 dose in 2014 and 2015 and then decreased at the K_2 dose (Table 9). WP values ranged from 6.29 kg m^{-3} (I_{125}) to 6.95 kg m^{-3} (I_{75}), 5.22 kg m^{-3} (I_{125}) to 5.42 kg m^{-3} (I_{75}), and 7.35 kg m^{-3} (I_{125}) to 8.18 kg m^{-3} (I_{75}) in 2012, 2014, and 2015, respectively, according to irrigation amounts (Table 9).

In all growing seasons, the K_1I_{75} treatments had the highest WP and IWP values, while the K_0I_{125} treatments had the lowest WP and IWP. However, as the irrigation volume was increased with the same K dose, the WP and IWP values decreased. In 2012, 2014, and 2015, the WP ranged from 5.26 to 7.68 kg m^{-3}, 4.77 to 6.22 kg m^{-3}, and 6.76 to 9.54 kg m^{-3}, respectively. In 2012, 2014, and 2015, the IWP ranged from 6.84 to 11.74 kg m^{-3}, 8.04 to 13.27 kg m^{-3}, and 8.36 to 13.48 kg m^{-3}, respectively (Table 9). The lowest irrigation level, on the other hand, resulted in a lower overall fruit yield and a lower quality of pomegranate. These findings are in line with the findings of Meshram et al. (2010, 2019), Dinc et al., (2018),

Table 9 The WP and IWP of pomegranate under different treatments in the experimental years

The analysis of variance	WP, kg m^{-3}			IWP, kg m^{-3}		
P values	2012	2014	2015	2012	2014	2015
Potassium (K)	<.0001**	0,0003**	<.0001**	<.0001**	0,0003**	<.0001**
Irrigation (I)	<.0001**	<.0001**	<.0001**	<.0001**	<.0001**	<.0001**
K x I	<.0001**	<.0001**	<.0001**	<.0001**	<.0001**	<.0001**
K dose (K)						
K_0	5.55c	4.79c	6.97c	7.81c	9.06c	9.17c
K_1	7.07b	6.04a	8.58a	10.00b	11.50a	11.39a
K_2	7.11a	5.13b	7.51b	10.09a	9.80b	10.05b
LSD (0.05)	0.013	0.039	0.013	0.014	0,021	0.016
Irrigation level (I)						
I_{75}	6.95a	5.42a	8.18a	10.65a	11.57a	11.55a
I_{100}	6.49b	5.33b	7.53b	9.05b	9.92b	9.86b
I_{125}	6.29c	5.22c	7.35c	8.21c	8.86c	9.19c
LSD(0.05)	0.019	0.034	0.008	0.011	0.015	0.015
K x I interaction						
K_0I_{75}	5.94 g	4.83f	7.33f	9.04f	10.29d	10.27c
K_0I_{100}	5.46 h	4.78 fg	6.82 g	7.55 h	8.84 g	8.87f
K_0I_{125}	5.26i	4.77 g	6.76 h	6.84i	8.04i	8.36 g
K_1I_{75}	7.68a	6.22a	9.54a	11.74a	13.27a	13.48a
K_1I_{100}	6.92e	6.10b	8.35b	9.66d	11.35b	10.91b
K_1I_{125}	6.60f	5.81c	7.85c	8.61 g	9.86e	9.78d
K_2I_{75}	7.24b	5.20d	7.67d	11.16b	11.16c	10.91b
K_2I_{100}	7.08c	5.11e	7.44e	9.93c	9.57f	9.81d
K_2I_{125}	7.01d	5.09e	7.43e	9.19e	8.66 h	9.43e
LSD(0.05)	0.034	0.060	0.014	0.019	0.026	0.026
CV %	0.29	0.63	0.01	0.11	0.14	0.14

Letters indicate significant differences at $^{*}P<0.05$; at $^{**}P<0.01$

and Martínez-Nicolas et al. (2011) who stated that lower pomegranate yield values resulted in lower WP values. WP and IWP are considered significant pointers for determining on-farm water management and supporting decisions at local and at farm levels. On the contrary, Intrigliolo et al. (2012, 2013) stated that the yield was not affected by 50% reduced irrigation in pomegranate trees, resulting in significant water savings and increased WP and IWP in Spain. The use of deficit irrigation can be a method to decrease water use and improve agricultural sustainability in arid and drought-stricken areas. As a result, a higher K dose (K_2) with an I_{75} irrigation level is not recommended for drip-irrigated pomegranate production in the area. Our findings on WP and IWP are generally consistent with the research findings described above.

Cracking rate in pomegranate

Fruit cracking is a physical breakdown of the fruit peel that appears as cracks in the peel or cuticle of some fruits or splitting, a more severe type of splitting that penetrates deeply into the pulp. Fruit cracking in pomegranate started to appear at the end of August–early September under deficit irrigation treatment (I_{75}) at K_0 dose and increased in the period until harvest. In cases where potassium was applied, fruit cracking occurred close to harvest due to the onset of rainfall and changes in daytime temperatures. Table 10 shows the cracking rate of pomegranate under various treatments. The study of variance revealed that there was a substantial impact on the relationship between K dose and irrigation level on pomegranate cracking rate in 2012 ($P<0.01$), 2014, and 2015 ($P<0.05$) (Table 10). The LSD test was used to classify means at the 1 and 5% likelihood levels. In 2012, 2014, and 2015, the cracking rate ranged from 7.69 to 18.12%, 7.31 to 15.36%, and 6.88 to 13.53%, respectively. Cracking frequencies were higher in K_0 plots than in K_1 and K_2 plots in experimental years. The cracking rate of water-stressed pomegranate exposed to K applications (K_1I_{75}, K_2I_{75}) was remarkably lower than those of water-stressed plants without K applications (K_0I_{75}) (Table 10). This may be an outcome of the role of K in the arrangement of the stomatal closing and the resultant effect of the low ratio of photosynthesis. As a stress palliative, potassium alleviated the negative influence of water stress by adjusting or curing stomatal conductance, photosynthetic rate, and pomegranate development by supporting the source-to-sink relation. This indicated that the rise in potassium dose supported the development and pomegranate yield, reducing the cracking ratio, and the rise in irrigation amount enhanced the efficacy of K fertilizer (Table 7, 9, 10). In terms of irrigation levels, low cracking rates and high yield were found generally in I_{100} and I_{125} irrigation treatments in this experiment. Since irrigation changes soil water conditions, modifying irrigation practices can change the frequency of the cracking rate. In all experimental years, the maximum and minimum cracking rates were found in the K_0I_{75} and K_2I_{75} applications. When cracking rates were examined according to irrigation levels in each potassium dose, cracking rates decreased from I_{75} to I_{100} irrigation level, and then increased from I_{100} to I_{125} irrigation level in 2012, 2014, and 2015. In general, there was no statistical difference in terms of cracking rate in pomegranate between I_{100} and I_{125} treatments in each potassium dose. For 3 years, water stress greatly improved the cracking rate in pomegranates (Table 10). Our findings were pretty in concord with the prior studies managed by Khattab et al. (2011), Seidhom and El-Rahman (2011), and Yılmaz and Ozguven (2019). During 2012, 2014, and 2015, the SWC in the I_{100} and I_{125} plots of each K dose stayed above 50% of available water (AW) in most of the pomegranate growth stages. Therefore, the I_{100} and I_{125} treatments performed an appropriate soil water condition for the pomegranate. Similarly, insufficient irrigation practice in sandy soils causes excessive flower loss and fruit cracking during harvest time (Yılmaz et al. 1995).

Rind thickness in uncracked and cracked fruit on pomegranate

Rind thickness in uncracked fruit on pomegranate

According to the analysis of variance administered to the results obtained in 2012, 2014, and 2015, the rind thickness of uncracked fruit on pomegranate at the 5% level was not statistically influenced by the interaction of K doses and irrigation levels. The rind thickness of fruit on pomegranate was significantly influenced ($P<0.05$) by the K doses in experimental years (Table 11). The rind thickness of uncracked fruit on pomegranate varied between 3.69 and 4.26 mm in 2012, 3.84–4.30 mm in 2014, and 3.36–3.92 mm in 2015.

Typical symptoms of K deficiency in pomegranate are thin peels which result in an increased cracking ratio. When K doses in all experiment years were analyzed, rind thickness values were measured to be at the lowest level in the K_0 treatment. The rind thickness increased with the increasing amounts of K dose in the treatments, in which the greatest rind thickness was attained from the K_2 treatment (4.26, 4.30, and 3.92 mm) in all years (Table 11). According to Gill et al. (2012), a higher potassium dosage increased fruit color as well as rind thickness and aril weight. In an experiment conducted in Solapur, India, it was discovered that different NPK combinations had a major effect on rind thickness. Maximum rind thickness (3.5 mm) was registered with the highest dose of K (300 g plant^{-1}) (Anonymous 2016). The findings of this research are consistent with those found in the literature. Al-Obeed (2001) found that adding 1 kg potassium sulfate tree^{-1} caused a significant increase in the

Table 10 LSD grouping related to cracking rate in irrigation level and K dose interaction

K dose	Irrigation levels	Cracking rate (%)		
		2012**	2014*	2015*
K_0	I_{75}	18.12 a	15.36 a	13.53 a
	I_{100}	10.19 cd	9.90 b	9.75 bc
	I_{125}	11.19 bc	10.71 b	10.19 bc
K_1	I_{75}	13.25 b	11.10 b	11.24 ab
	I_{100}	9.34 cd	8.62 bc	7.75 cd
	I_{125}	9.85 cd	9.34 bc	8.05 cd
K_2	I_{75}	7.69 d	7.31 c	6.88 d
	I_{100}	9.11 cd	9.09 bc	9.28 bd
	I_{125}	9.48 cd	8.69 bc	8.85 bd
		LSD(0.01) = 2.60	LSD(0.05) = 3.20	LSD(0.05) = 2.69

Source	df	Prob	Source	df	Prob	Source	df	Prob
2012	2	0.0051**	2014	2	0.0093**	2015	2	0.0238**
K			K			K		
I	2	0.0007**	I	2	0.0710**	I	2	0.0738**
KxI	4	0.0010**	KxI	4	0.0401*	KxI	4	0.0160*

K_0, K_1, and K_2: potassium doses, I_{75}, I_{100}, and I_{125}: irrigation levels

*Significant at $P < 0.05$, **Significant at $P < 0.01$

Table 11 The rind thickness of uncracked fruit in different K doses and the rind thickness of cracked fruit in different irrigation levels on pomegranate (2012, 2014, and 2015)

	Rind thickness of uncracked fruit (mm)				Rind thickness of cracked fruit (mm)			
	Potassium dosages			lsd (0.05)	Irrigation levels			LSD (0.001)
	K_0	K_1	K_2		I_{75}	I_{100}	I_{125}	
2012	3.69 b	4.02 ab	4.26 a	0.41	3.25 b	3.82 a	3.91 a	0.45
2014	3.84 b	4.16 a	4.30 a	0.23	3.67	3.95	3.99	0.36
2015	3.36 b	3.71 ab	3.92 a	0.42	3.18 b	3.55 a	3.57 a	0.34

Source	df	Prob	Source	df	Prob	Source	df	Prob	Source	df	Prob	Source	df	Prob	Source	df	Prob
2012			2014			2015			2012			2014			2015		
K	2	0.0433*	K	2	0.0132*	K	2	0.0498*	K	2	0.2147 ns	K	2	0.0306*	K	2	0.4115 ns
I	2	0.07715 ns	I	2	0.4954 ns	I	2	0.2001 ns	I	2	0.0154*	I	2	0.0848 ns	I	2	0.0470*
KxI	4	0.4004 ns	KxI	4	0.8538 ns	KxI	4	0.9315 ns	KxI	4	0.0938 ns	KxI	4	0.9945 ns	KxI	4	0.7097 ns

K_0, K_1, and K_2: potassium doses, I_{75}, I_{100}, and I_{125}: irrigation levels

*Significant at $P<0.05$, *ns* non-significant

Table 12 Fruit number and fruit weight of uncracked fruit in different irrigation levels on pomegranate (2012, 2014, and 2015)

Years	Fruit number of uncracked fruit (no)				Fruit weight of uncracked fruit (g)			
	İrrigation levels			LSD (0.05)	Irrigation levels			LSD (0.05)
	I_{75}	I_{100}	I_{125}		I_{75}	I_{100}	I_{125}	
2012	105 b	108 ab	114 a	7.38	415.8 b	428.2 b	473.1 a	36.6
2014	106 b	110 ab	116 a	7.43	386.9 b	398.6 b	434.3 a	27.2
2015	115 b	118 b	127 a	6.51	422.5 b	442.6 a	486.1 a	47.4

Source	df	Prob	Source	df	Prob	Source	df	Prob	Source	df	Prob	Source	df	Prob	Source	df	Prob
2012			2014			2015			2012			2014			2015		
K	2	0.8545 ns	K	2	0.9698 ns	K	2	0.0543 ns	K	2	0.6694 ns	K	2	0.0757 ns	K	2	0.2264 ns
I	2	0.0430*	I	2	0.0277*	I	2	0.037*	I	2	0.0127*	I	2	0.0067**	I	2	0.0665*
KxI	4	0.6399 ns	KxI	4	0.7591 ns	KxI	4	0.1534 ns	KxI	4	0.7994 ns	KxI	4	0.5413 ns	KxI	4	0.965 ns

I_{75}, I_{100}, and I_{125}: irrigation levels

*Significant at $P<0.05$, **Significant at $P<0.01$

rind thickness as compared with 2 kg tree^{-1} and the control treatments. According to Dhillon et al. (2011), K treatment marginally increased the rind %, suggesting the position of these fertilizer nutrients in increased rind thickness in pomegranate. Yılmaz and Ozguven (2019) determined that the rind of healthy fruits contains higher levels of potassium than the rind of cracked fruits.

Rind thickness in cracked fruit on pomegranate

Results showed that the rind thickness of cracked fruit was significantly influenced ($P < 0.05$) by the irrigation levels in 2012 and 2015. It varied between 3.25 and 3.91 mm in 2012 and 3.18–3.57 mm in 2015. Based on the LSD test (Table 11), the rind thickness of cracked fruit on pomegranate increased with the increasing amounts of irrigation in the treatments, in which the greatest rind thickness of cracked fruit was attained from the I_{125} (3.91 and 3.57 mm) treatment in both years. I_{75} treatment was the last group (3.25 and 3.18 mm) in both years. Pomegranate fruits obtained from an insufficient irrigation regime (I_{75}) during the entire development period had a significant thinning of their rind at the end of the ripening cycle, resulting in fruit cracking. Similarly, many researchers also indicated that deficit irrigation induces a considerable thinning in the rind thickness of pomegranate (Mellisho et al. 2012; Galindo et al. 2014; Saei et al. 2014; Marathe et al. 2016; Selahvarzi et al. 2017).

The timing of water stress can affect fruit cracking. During the ripening period of the pomegranates, especially at the deficit irrigation level (I_{75}) at each K dose, the soil water values are below 50% of available water in all three experimental years, and thus, fruit cracking increases due to plant–water relations. When exposed to water tension, the mechanical properties of the peel change, with the peel's extensibility continuing to decrease. These variations could express the sensitivity of pomegranate fruits to cracking. These outputs are in line with Intrigliolo et al. (2013) who determined that while deficit irrigation at the beginning of the season in the first phase of fruit development reduces the formation of fruit cracking in pomegranate, on the contrary, fruit cracking increases with the sudden change of soil water in later development periods and consequently on plant–water relations.

Fruit number and fruit weight in uncracked fruit on pomegranate

The effect of K doses on fruit weight and fruit number of pomegranates was not determined statistically in 2012, 2014, and 2015. Irrigation levels resulted in a remarkably ($P < 0.05$) different fruit number per tree as well as fruit weight in three growing seasons. Uncracked fruit weight on pomegranate rose as the amount of irrigation water increased (Table 12). The number of fruits per tree is positively associated with pomegranate fruit yield. An increase in fruit number per tree is the most important factor in the pomegranate fruit yield rising. Uncracked fruit numbers on pomegranate trees rose with increasing irrigation amounts in the treatments considered. The highest fruit number (114, 116, and 127) was acquired from the I_{125} treatment in three growing seasons (Table 12). I_{75} treatment ensured the lowest fruit number on pomegranates (105, 106, and 115) in the 2012, 2014, and 2015 growing seasons.

The highest fruit weight averaging 464.5 g was acquired in I_{125}, followed by the I_{100} treatment, and the lowest fruit weight was acquired from the I_{75} treatment at 408.4 g in 3 experimental years (Table 12). Also, fruit weight is closely associated with a shortage of soil water in the plant root zone; when the soil water deficit in the root zone rises, there is a loss in turgidity and a reduction in the growth and fruit weight of pomegranate. Plant growth was reduced in the presence of moderate water stress in the I_{75} treatment, resulting in a smaller final fruit size and a lower overall fruit yield. In addition, the results showed that the available soil water in the root zone should not fall below 50% during the growing period to avert poor fruit size and shape and increase pomegranate yield for each K dose during the growing season in all experimental years. Adiba et al., (2021) discovered distinct variations in pomegranate cultivar responses to water stress. In Morocco, the most common results of water stress were fruit yield and fruit weight on pomegranates.

Net economic return on pomegranate

The economic assessment was completed using averages of 3-year data based on crop production costs, annual irrigation system cost, labor and operation cost of irrigation, water cost, and K fertilizer cost, and the outcomes are indicated in Table 13. Concerning economic assessment, the highest net return was acquired as US$7141 ha^{-1} for the K_1I_{125} treatment followed by the K_1I_{100} treatment (US$6531 ha^{-1}). When comparing deficit irrigation treatment (I_{75}) at different K doses, the K_0I_{75} treatment provided the lowest net income. The lowest irrigation level (I_{75}) ensured diminished net return in each K dose. It was recorded that there was a notable difference in terms of net return between the K doses and irrigation levels. Net income values decreased due to the decrease in irrigation water at all K doses. Moreover, the K_1I_{125} and K_1I_{100} treatments ensured remarkably more net returns compared to the other treatments (Table 13). In the experimental treatments, the total cost of production increased markedly with the increase in the amount of irrigation water and K fertilizer dose. Whole production costs of the K1I125 treatment comprise the following factors, with the related percentage of the whole cost in brackets: crop production (46.3%), irrigation system (12.5%), labor

Table 13 Comparative assessment of the combined economic analysis under different K doses and irrigation levels

Treatments	Irrigation water (mm) (1)	Irrigation water (m^3 ha^{-1}) (2)	Irrigation duration for the irrigation season (h) (3)	Labor cost for irrigation ($ h^{-1}) (4)	Total cost for irrigation labor ($) (5) (3×4)	Water price ($ m^{-3}) (6)	Water cost ($ ha^{-1}) (7) (2×6)	Crop production costs ($ ha^{-1}) (8)
K_0I_{75}	255	2553	128	3	383	0.3	766	2322
K_oI_{100}	329	3290	165	3	494	0.3	987	2322
K_oI_{125}	403	4030	202	3	605	0.3	1209	2322
K_1I_{75}	255	2553	128	3	383	0.3	766	2322
K_1I_{100}	329	3290	165	3	494	0.3	987	2322
K_1I_{125}	403	4030	202	3	605	0.3	1209	2322
K_2I_{75}	255	2553	128	3	383	0.3	766	2322
K_2I_{100}	329	3290	165	3	494	0.3	987	2322
K_2I_{125}	403	4030	202	3	605	0.3	1209	2322
Treatments	Irrigation system cost for 1 ha ($ h^{-1}) (9)	Yearly cost for the irrigation system ($ ha^{-1}) (10) (9/6 years)	K fertilizer cost ($ ha^{-1}) (11)	Total cost for 1 year ($ ha^{-1}) (12) (5 + 7 + 8 + 10 + 11)	Pomegranate yield (kg ha^{-1}) (13)	Pomagranate sales price ($ kg^{-1}) (14)	Gross income per ha ($ ha^{-1} $year^{-1}$) (15) (13×14)	Net income ($ ha^{-1} $year^{-1}$) (16) (15–12)
K_0I_{75}	3760	627	0	4097	25193	0.32	8062	3965
K_oI_{100}	3760	627	0	4429	27740	0.32	8877	4448
K_oI_{125}	3760	627	0	4762	31270	0.32	10006	5248
K_1I_{75}	3760	627	251	4348	32787	0.32	10492	6144
K_1I_{100}	3760	627	251	4680	35033	0.32	11211	6531
K_1I_{125}	3760	627	251	5013	37980	0.32	12154	7141
K_2I_{75}	3760	627	515	4612	28297	0.32	9055	4443
K_2I_{100}	3760	627	515	4944	32507	0.32	10402	5458
K_2I_{125}	3760	627	515	5277	36687	0.32	11740	6463

(12.1%), water (24.1%), and K fertilizer cost (5.0%) over the 3-year study. In areas where access to irrigation water is pricey or where less water is available than needed, K_1I_{100} treatment is a plausible option. In this study, 25.0% savings in irrigation water ensured a 7.8% decrease in pomegranate yield and an 8.5% decrease in net income compared to 3-year average values (Table 13). According to Maity et al. (2022), the use of 150 g of bio-mineral fertilizer per tree on pomegranate significantly enhanced fruit yield, quality, and farm income and also developed the cost–benefit ratio.

Conclusions

Potassium doses and irrigation levels remarkably influenced the growth, yield, and quality of pomegranate, and had interaction impacts on soil water delivery, water usage, fruit yield, WP, and IWP, cracking rate, rind thickness, fruit weight, fruit number, and net economic return. Ensuring the effective use of irrigation water with suitable fertilizers dose will go a long way in addressing the global water crisis shortly, thereby decreasing waste. The outputs displayed that K_1I_{125} treatment, which achieved the maximum fruit yield and net return, can be suggested for regions with adequate water conditions, and in case of irrigation water is pricey or water provides less than the requirement K_1I_{100} treatment could be a fine option on pomegranate production. Also, the K_1I_{100} irrigation strategy is an effective method for conserving water while improving WP and IWP under water-scarcity status. Furthermore, higher irrigation levels (I_{125}) and excessive K fertilizer dose (K_2) not only diminished WP and IWP but also squandered fertilizer resources. We may infer that pomegranate yields in Turkey's Eastern Mediterranean can be maintained or developed under drip irrigation conditions with controlled, reduced irrigation amounts without compromising productivity. The interaction impact of K dose and irrigation level had an expressive effect on the cracking rate of pomegranate during the three growing seasons. While K fertilizer performs a very important role in high yield and quality increment, the negatory impact of water stress on cracking rate decreased with rising K dose. The results indicated that K fertilization caused 8.3–27.7% less fruit cracking in K_1 treatments and 4.8–57.5% less in K_2 treatments compared to K_0 under the same irrigation levels, and the best positive effect of K application was found in K_2I_{75} over the 3-year study. Deficit irrigation treatment (I_{75}) reduced pomegranate fruit yield due to a reduction in fruit weight and fruit number during a 3-year experimental period. One of the most helpful impacts of the K application as compared to Ko was the enhancement of rind thickness on uncracked fruit and a decrease in fruit cracking. As a result, the positive effect of the appropriate K dose on the uncracked fruit and the suitable irrigation level on the rind thickness in the cracked fruit statistically significantly reduced the cracking rate in pomegranate fruit. The outcomes of this study are of high importance for the improvement of irrigation water and K fertilizer management, the implementation of appropriate irrigation and potassium fertilizer management systems, the highest net returns, and benefit to decision-makers on pomegranate under drip irrigation in similar arid and semi-arid pomegranate areas.

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Author contributions Author contributions sectionAll authors contributed to the study's conception and experimental design. Material preparation, data collection, analysis, and designed the figures and tables were performed by B.I., S.M.S., C.Y. and M.U.. All authors provided critical feedback and helped shape the research, analysis, and manuscript, and also approved the final manuscript.

Data Availability Data availability is appropriate.

Declarations

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

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